Engineering Geology of Alpine Tunnels: Past, Present and Future

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This lecture will provide a review of engineering geological contributions to the design and construction of deep tunnels during the last 150 years. The progress and current status in engineering geological approaches and theoretical understanding of observed phenomena and geological hazards will be critically discussed and documented with a large number of examples of traffic tunnels constructed through the European Alps. The lecture will close with an outlook into unresolved key issues that should be addressed in future interdisciplinary research and technology development initiatives.

First traffic tunnels through the European Alps were constructed as part of transalpine railway lines in the second half of the 19th century and the beginning of the 20th century. The length of these tunnels ranged between 10 km and 20 km with maximum overburden of 700 m to 2100 m. The most important engineering geological contributions to the design of these tunnels were predictive longitudinal geological sections. As deep rotary drilling technologies were not available at that time, geological surface mapping and drilling of pilot tunnels were the most important methods for deep tunnel design. On the other hand the second half of the 19th century was the period when major concepts of Alpine tectonics – such as nappe tectonics - were developed. Therefore some tunnel projects, like the Simplon Base Tunnel, were confronted with strongly differing geological predictions and public debates lasting several decades. Major geological catastrophies like the collapse of Lötschberg Crest Tunnel in 1908 were related to fundamental misinterpretations of geological processes. In the 19th century the engineering geological documentation of the encountered conditions was often done with great care and lead to important descriptions of many types of geological hazards we are confronted with today in deep tunneling. However, interpretations of high water inflows, strongly squeezing ground and rock bursts were incomplete or misleading as theoretical knowledge of rock stresses, rock mass properties and groundwater hydrodynamics were very limited.

In the second half of the 20th century the increase in road traffic lead to a period of intensive road tunnel constructions through the Alps. In contrast to the century before, engineering geological tunnel design could be based on a comprehensive description of Alpine tectonics, deep drilling and geotechnical description of heterogeneous (fractured) rock masses. Nevertheless unexpected ground behavior sometimes led to severe accidents and delays. Most of these adverse geological conditions were related to brittle faulting, karstification and deep seated landsliding. In addition environmental impacts such the drying out of springs through tunnel drainage became an important issue.

The Alpine tunnels constructed today are important components of high-speed transalpine railway corridors. They cross the mountain belt at the elevation of the main cities and basins located to the north/west and south/east of the Alps and are therefore longer (up to 57 km) and deeper (up to 2500 m) than all tunnels constructed in the centuries before. The majority of the applied engineering geological methods used to design these tunnels have been descriptive and very similar to the road tunnels constructed in the second half of the 20th century. The main differences in the portfolio used to design these tunnels are related to the exploration methods, which today also regularly include surface and borehole based geophysical investigations. However, many geophysical methods applied during the preliminary investigations or subsequently during construction have not met their goals in complex Alpine tectonic settings. During the design stages the important experience of the professional engineering geologist was often weighted higher than fundamental understanding of the rock mass and groundwater behaviour. This led to some important surprises during tunnel construction, because the rock mass response does not change linearly with increasing depth or overburden.

The major geological problems as encountered today relate to the prediction and behaviour of larger faults at depth, heat transport in heterogeneous fractured rock masses, the primary stress conditions, stress-induced tensile failure of hard rocks, shear strength and squeezing of weak rocks (mainly fractured schists and phyllites), karstification of evaporites and limestones in relation to regional groundwater circulation systems, and large scale hydromechanically coupled processes leading to long lasting surface deformations. Current understanding and ongoing research of these issues is presented in detail in order to assist the practitioner in arriving at more economical solutions for future deep tunnels.

Today the prediction of the location of faults intersecting a deep long tunnel is based on geomorphological mapping, aerial photo or digital terrain model analysis. Most of these techniques reliably capture steeply inclined faults but not shallow angle thrusts. Shallow angle and brittle thrust faults can cause severe problems for TBM excavations. On the other hand, metamorphic shear zones at the base of major Alpine nappes, don’t cause severe stability problems. The fault architecture, orientation and thickness play a key role for water inflow, squeezing and tunnel face stability.

Deep tunnels are confronted with temperatures much higher than the allowed working conditions and have to be cooled during construction and operation. The appropriate prediction of these tunnel temperatures can not be based on heat conduction alone - heat advection by flowing groundwater needs to be taken into account, even when the tunnel is not confronted with large water inflows.

Primary stresses are difficult to predict for deep and long Alpine tunnels and non-uniform stress fields with either subvertical or subhorizontal major principal stresses have to be anticipated. Conventionally it is assumed that critical stress conditions develop at tunnel locations of high overburden. However, significant spalling and rock bursting has also been observed when tunnels are excavated at shallow depth below Alpine valleys. This indicates that topographic effects and erosion/ unloading during the Quaternary significantly impacts the primary stress field in the upper hundreds of metres. Even though the Central Alps show ongoing uplift and moderate seismic activity, tectonic stresses are not evident.

Spalling as a tensile failure mechanisms under low confinement has been studied during the last decade intensively within the framework nuclear waste and mining programs but only rarely applied to deep tunneling. Therefore, even though severe spalling could have been predicted for a critical depth of 1500 m and in extreme situations already below 700 m of overburden, spalling of hard rocks has been underestimated during the design of several new Alpine base tunnels. Spalling and subsequent rock mass strength degradation at the tunnel face causes significant difficulties for hard rock TBMs which are worsened when the foliation is subparallel to the tunnel face or when weak fault zones interact with the stress relaxation zone around the tunnel excavation. When weak zones run parallel to the tunnel axes deep-seated unravelling can occur even if the rock mass initially is massive to moderately jointed.

Since the 19th century many deep tunnels have been confronted with large convergence and strong squeezing resulting from tectonized schists or phyllites, often containing graphite. However the same tectonic units can behave in completely different ways when intersected by tunnels at similar depth along strike of the same tectonic unit. Understanding the rock mechanical process of squeezing requires detailed insights of the initial rock fabric (resulting from multiple pre-alpine and alpine deformation periods) and mineralogy (affected by various degrees of metamorphic overprint). New investigations demonstrate that direct shear tests with constant normal stiffness (not normal load) are required to reproduce the stress and stiffness conditions around underground excavations and understand the corresponding failure processes. Such tests with servo-hydraulic testing equipment show failure and deformation mechanisms composed of complex interactions between sliding, friction, dilation and cohesion.

Dissolution and transformation processes in limestones, dolomites, anhydrites, and rauhwackes can lead to highly transmissive solution voids (karst pipes) or unstable ground conditions (sugar grained dolomites). Current elevations of major receiving streams control the depth of active karst systems. For deep seated tunnels past groundwater circulation systems and fluvial erosion levels play a critical role in defining the maximum depth of ancient karstification. Such systems can have formed in late Tertiary or Quaternary and might be filled and clogged with fine-grained sediments which dramatically reduce water conductance and tunnel inflows. Understanding the late and post Alpine geological history can play a critical role for the identification and the design of counter measures for such geological hazards.

In the last decade large-scale consolidation settlements have not only been observed in karstified limestones and marls but also above tunnels in crystalline rocks of the Central Alps. Up to 120 mm of settlement has been observed above the Gotthard A2 Highway Tunnel, and so far transient settlements in the range of 50 mm have been detected above the Gotthard Base Tunnel near Sedrun. The consolidation in these examples is related to tunnel drainage and pore pressure reductions in the rock mass. Although these settlements may appear to be small compared to those experienced in more compliant porous media, they are large enough to adversely affect the structural integrity of sensitive concrete structures on the surface (e.g. thin-arch concrete dams). New 4D surface monitoring data acquired above the Gotthard Base Tunnel allows the understanding of long term transient and complex 3D deformation patterns evolving over lateral distances of several kilometres along deep Alpine tunnels, from which adequate mitigation measures can be derived.

The review of engineering geological aspects of deep Alpine tunnels constructed since the 19th century shows that progress depends on experience, technological developments, and – last but not least - our ability to understand our observations. Understanding structurally or stress/strain controlled deformation and failure is a key for future developments in engineering geology as applied to underground excavations. Most geologists are equipped with the necessary descriptive skills to capture the complexity and heterogeneity of geological materials, but they often lack the required understanding of physical processes driving the rock and rock mass response under the complex mechanical and hydraulic conditions around deep underground excavations. Therefore future research in ground engineering has to be interdisciplinary, quantitative, and based on carefully designed field monitoring programs and sophisticated lab tests, supported by realistic numerical models capturing the essential geological components and physical relationships.

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